Mid Jurassic pyroclastics of the Mawson Formation in the Prince Albert Mountains: products of phreatomagmatism

Senior Thesis

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by

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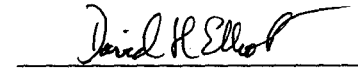

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Introduction

Volcanism is a process that shapes the Earth and its climates. It occurs in many different forms depending mainly upon magma composition and gas content. Both variables control whether volcanic activity is expressed as a quiet lava flow or an explosive burst of pyroclastics. Low viscosity magma allows gas to escape freely, resulting in lower volcanic explosivity. Traditional names, such as Hawaiian, Strombolian, Plinian, and Ultraplinian, have been applied to eruptive processes in order of increasing explosivity and area of particle dispersal (Fisher and Schmincke,1984).

Hawaiian eruptions are characterized by low viscosity basalt lavas which allow gas to escape readily. Blocky aa and smooth pahoehoe flows are both common. The Hawaiian process usually results in little to no pyroclastic debris (Fisher and Schmincke, 1984). Strombolian volcanism is distinguished by rhythmic gas explosions with some bombs. In addition, lava flows may be absent. This process typically results in the formation of cinder cones. Plinian eruptions are denoted by stratocones with ash clouds and widespread pyroclastic deposits. The high viscosity of the magma prevents sufficient degassing. The resulting pressure builds and is released in a large, explosive blast. The force of the eruption creates more fine tephra over a larger area of dispersal. The final group includes phreatic and phreatomagmatic eruptions. It is magma-water interaction, forming hydroclastic deposits, that makes these styles unique. The numerous eruptions are spaced over intervals of minutes to hours.

Phreatic eruptions are defined as steam explosions within the country rock over a magmatic heat source. In addition to these phreatic characteristics, phreatomagmatism

includes the disintegration of magma upon interaction with water, creating pancakes and spatter (Fisher and Schmincke, 1984). Although the effects of degassing magma versus groundwater vaporizing on the eruptive system is not completely understood, it is clear that together these variables cause pressure to build up over non-eruptive intervals.

The location of water with respect to the vent is an important feature that influences the mode of pyroclastic deposition. If water is added to the gas-particle mixture over the vent, the density of the cloud increases causing instability. The column will then collapse forming weakly bedded, cross-stratified, poorly sorted base- surge deposits. However, if the magma-water interaction occurs below the vent, slurries of juvenile pyroclasts; together with country rock torn from the walls of the vent; in an ash/mud matrix, may flow out of the vent. Reworked, older pyroclastic debris may also become incorporated into the mixture. The result is unbedded, unstratified deposits of tuff and tuff breccias. The grains comprising the unit will be rounded if there is active abrasion during transport. However, this rock/magma/ash mixture could also form a lahar which would move downslope from the vent. The deposit formed would also be unsorted, and unstratified, yet, would show no rounding of particles because of the passive mode of transport.

Regional Geology

The Permian-Triassic Victoria Group, which is the younger part of the Beacon Supergroup, is comprised of mainly sedimentary rocks (Fig. 1). These include tillites

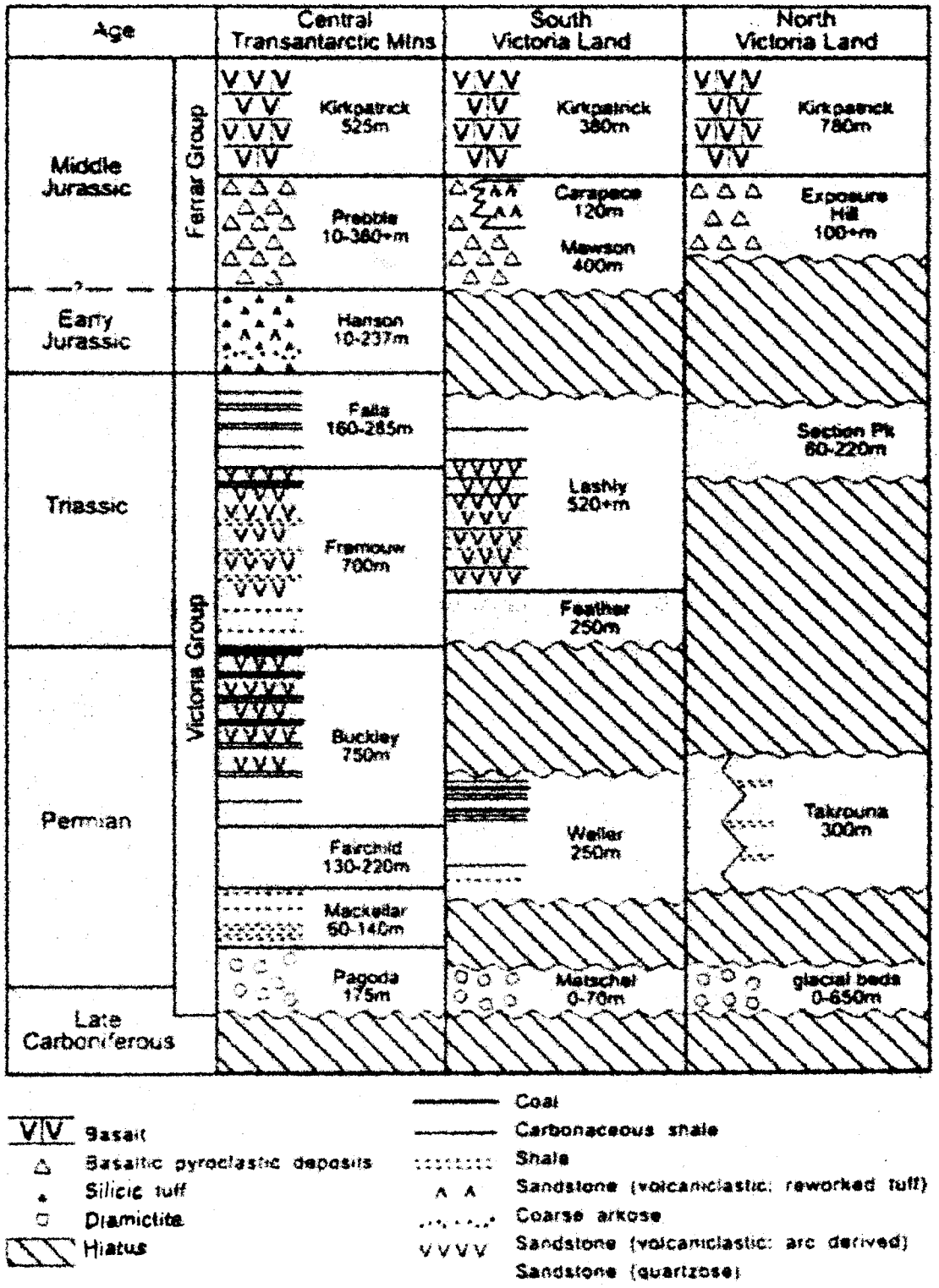

Age
Central Transantarctic Mtns
South Victoria Land
North Victoria Land
Middle Jurassic
Early Jurassic
Triassic
Permian
Late Carboniferous
Ferrar Group
Victoria Group
Kirkpatrick 525m
Prebble 10-380+m
Hanson 10-237m
Falla 160-285m
Fremouw 700m
Buckley 750m
Fairchild 130-220m
Mackellar 60-140m
Pagoda 175m
Kirkpatrick 380m
Carapace 120m
Mawson 400m
Lashly 520+m
Feather 250m
Weller 250m
Metschel 0-70m
Kirkpatrick 780m
Exposure Hill 100+m
Section Pk 60-220m
Takrouna 300m
glacial beds 0-650m
Basalt
Basaltic pyroclastic deposits
Silicic tuff
Diamictite
Hiatus
Coal
Carbonaceous shale
Shale
Sandstone (volcaniclastic: reworked tuff)
Coarse arkose
Sandstone (volcaniclastic: arc derived)
Sandstone (quartzose)

Figure 1

overlain by "post glacial shales" and non-marine quartz rich siltstones and sandstones that contain coal (Elliot, 1999). The youngest formation in the Beacon Supergroup, the Falla, is overlain by the silicic tuffs and interbedded volcaniclastic sandstones of the Early Jurassic Hanson Formation. The Hanson is then succeeded by Middle Jurassic igneous rocks of the Ferrar Group. This group includes the intrusive sills and dikes of the Ferrar Dolerite as well as the younger, extrusive pyroclastics which have been assigned to the Prebble, Mawson or Exposure Hill Formations. Finally, these tuffs and tuff breccias are overlain by the Kirkpatrick flood basalts of Mid Jurassic age.

Stratigraphy

The Mawson Formation in the Prince Albert Mountains is observable in a few scattered outcrops, including the site of 97-14 near Thomas rock (Fig. 2). None of these outcrops exceed 75 meters in height (Fig. 3) (Kyle, 1979; Worner, 1992; Elliot et al, 1997, Elliot, 1999). Kyle (1979) was the first to recognize the presence of tuff breccias in this region, and assigned them to the Mawson Formation. He defined this group of pyroclastics as breccias, lapilli tuffs and tuffs. In 1992 Worner interpreted similar rocks, which he referred to the Exposure Hill Formation, as "volcaniclastic breccia, lahars, hyaloclastites interlayered by pumice bearing tuffites as well as sand and siltstones." Through petrographic investigations, the pumice Worner mentioned was determined to be highly zeolitized basalt clasts and the possible ignimbrite layer was not observed. Finally, Elliot (1999) described the Mawson as primarily unbedded tuff breccia.

The first 30 meters of section 97-14 is dominated by tuff breccia with some tuff and lapilli tuff. The breccia is poorly sorted and unstratified. Volcanic rock fragments,

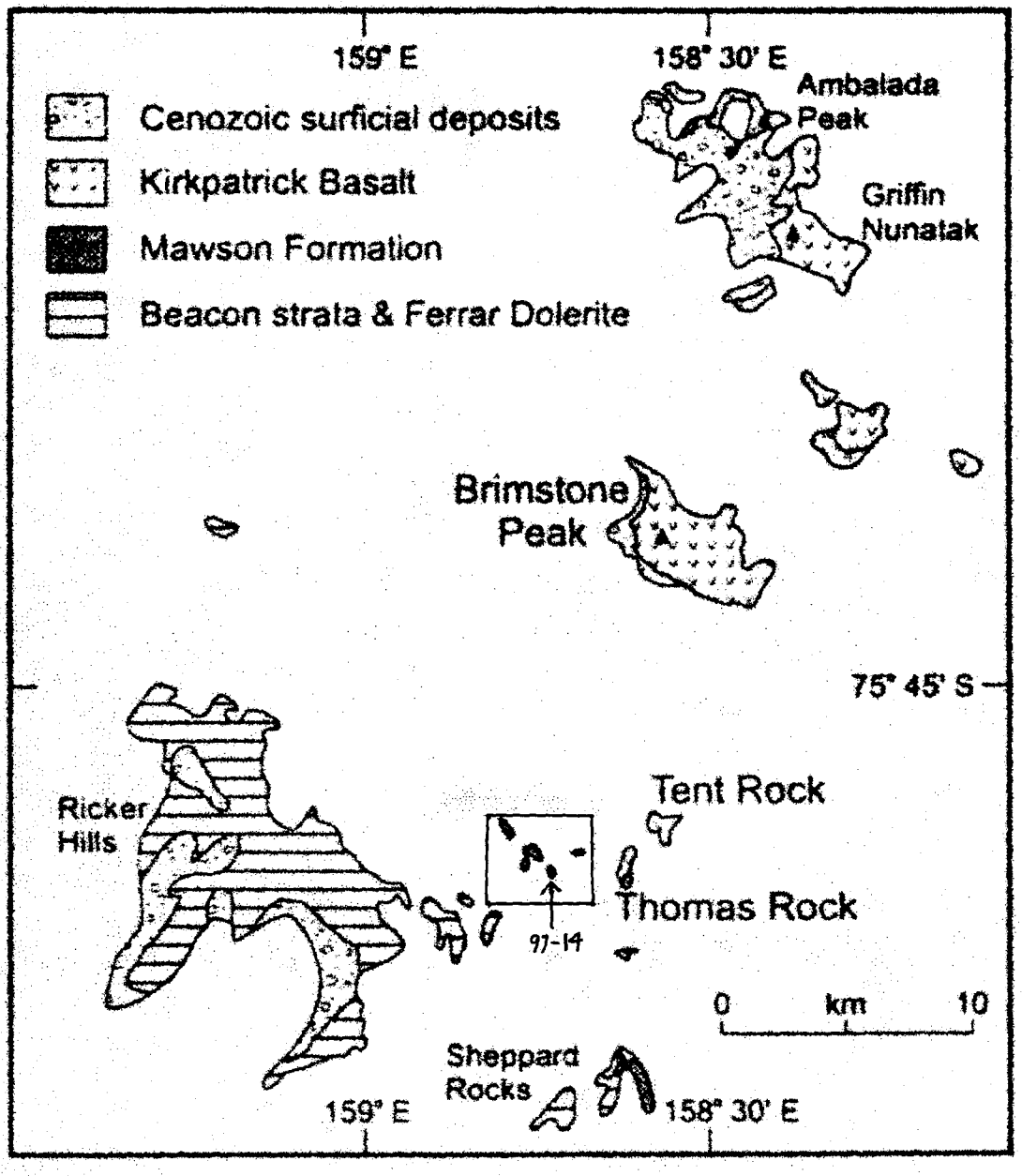
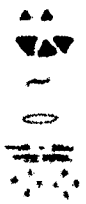

159° E
158° 30' E
Cenozoic surficial deposits
Kirkpatrick Basalt
Mawson Formation
Beacon strata & Ferrar Dolerite
Ambalada Peak
Griffin Nunatak
Brimstone Peak
75° 45' S
Ricker Hills
Tent Rock
Thomas Rock
97-14
0 km 10
Sheppard Rocks
159° E
158° 30' E

Figure 2

Mawson Formation



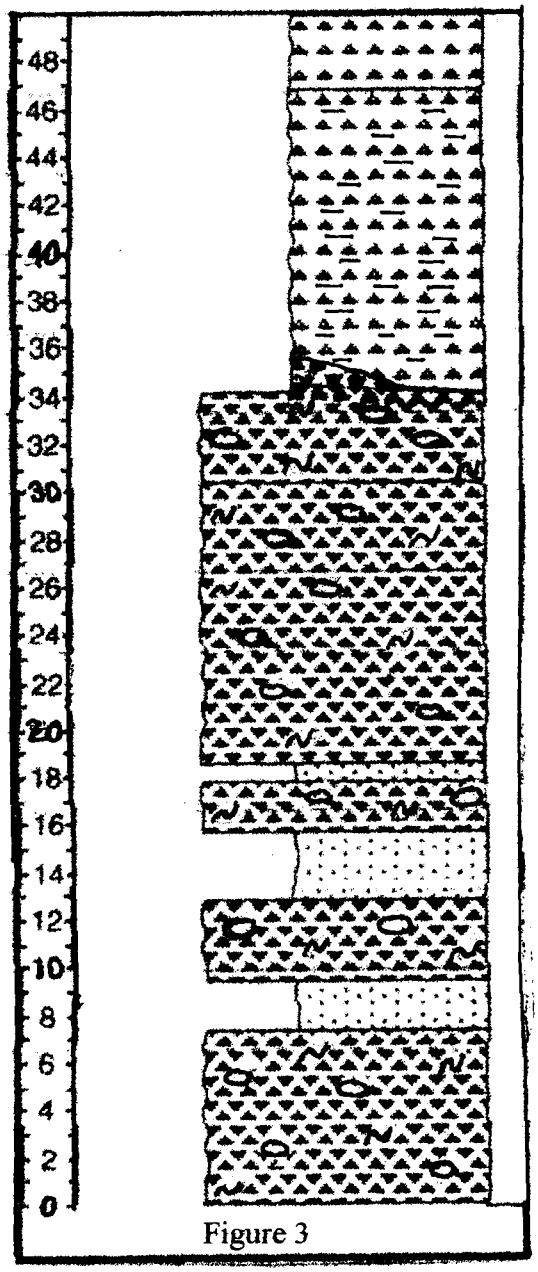


Figure 3

including tan and white altered basalt clasts, pancake basalt clasts, (up to 2 meter long) and spatter with wispy ends and tendrils are common throughout this section. Clasts indicating magma-wet sediment interaction were observed around 5.5 meters and 11 meters. First, in the form of a basalt "pancakes" wrapped around carbonaceous clasts, and second, a peperite clast where the magma has intruded sediment (Fig 4). Sedimentary rock fragments are common, including sandstones, siltstones and coaly shales (Fig 5). Clastic dikes were observed around 7.5, 12.6, and 18.4 meters. These dikes are more abundant in this area than any other Mawson outcrop.

Above 30 meters, basalt pancakes and shreds begin to diminish while dense basalt clasts and Beacon sandstone clasts increase in concentration. A bedded sequence of alternating tuff and lapilli tuff laps against a mound of coarse debris around 33 meters (Fig. 6 & Fig. 7). This unit shows no low angle cross stratification. Load casting as well as flame structures can be identified in the coarser layers. Weakly bedded tuff and lapilli tuff containing tan and white altered basalt fragments, dense basalt clasts and coaly shale fragments, persist until 47.6 meters.

There is an abrupt boundary between the weakly bedded tuff/lapilli tuff and the overlying unit. This unit begins at 47.6 meters and continues up to the summit at 50 meters. It is comprised of a massive, unbedded tuff. Although the matrix is very fine grained, the tuff contains numerous clasts of basalt and coaly shale.

Figure 5

Figure 4

Figure 6

Figure 7

Petrography

Thirty-three thins sections from the Mawson Formation near Thomas Rock were examined. These sections consisted of volcanic breccias, tuff breccias, tuffs, lapilli tuffs, basalt clasts, sandstone clasts, clastic dike sequences. Among the clastic grains, quartz was most abundant. In some instances quartz xenocrysts showed fractures due to heat shattering in the magma (Fig. 8). Pyroxene is abundant throughout most of the thin sections. Phyllosilicate was also common with muscovite rare but widespread (14-5B, 14-6, 14-9, and 14-17). Much of the brown phyllosilicate was secondary, replacing pyroxene, glass shards and basalt fragments. Occasional pyroxene pseudomorphs were noted where the crystal outline stands out against the secondary minerals (14-3A, 14-3B) (Fig. 9). Plagioclase and alkali feldspar are widespread as well. Microcline was identified on the basis of cross-hatched twinning and perthite was observed with characteristic exsolution blebs. Low percentages of pale green amphibole and blocky, anhedral garnet (Fig. 10) were common throughout many of the slides. Tourmaline occurred on one thin section (14-5B). Many slides contained rock fragments (14-3B, 14-9, 14-14, 14-18, 14-23, 12-29 and 14-33). Some sedimentary fragments include ragged coal clasts (Fig.11), and mudstone. A rhyolitic rock fragment was also observed (14-9).

Along with these clastic grains there are a wide variety of volcanic pyroclasts. The most abundant volcanogenic particle are glass shards. Brown-orange in color, due to secondary replacement by secondary phyllosilicate, these clasts include rectangular, platy shards and scalloped margins representing original bubble walls. (Fig. 13). Two major

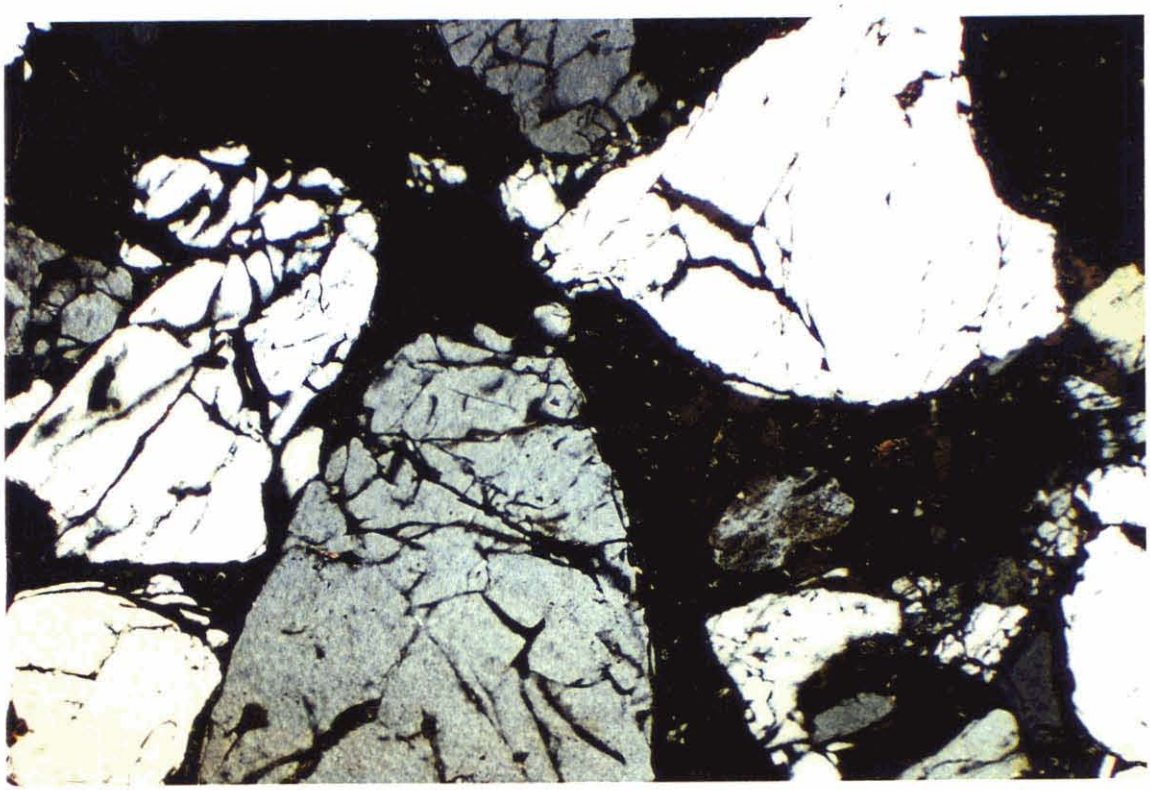
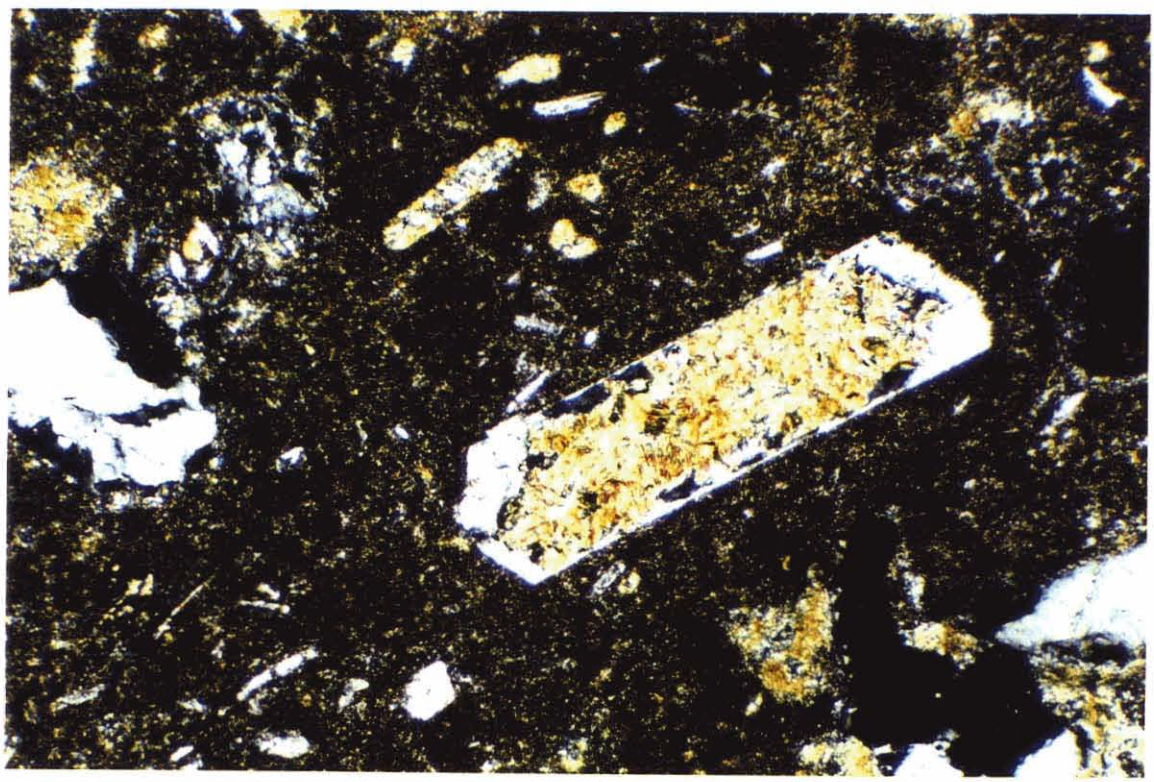


Figure 8

Figure 9



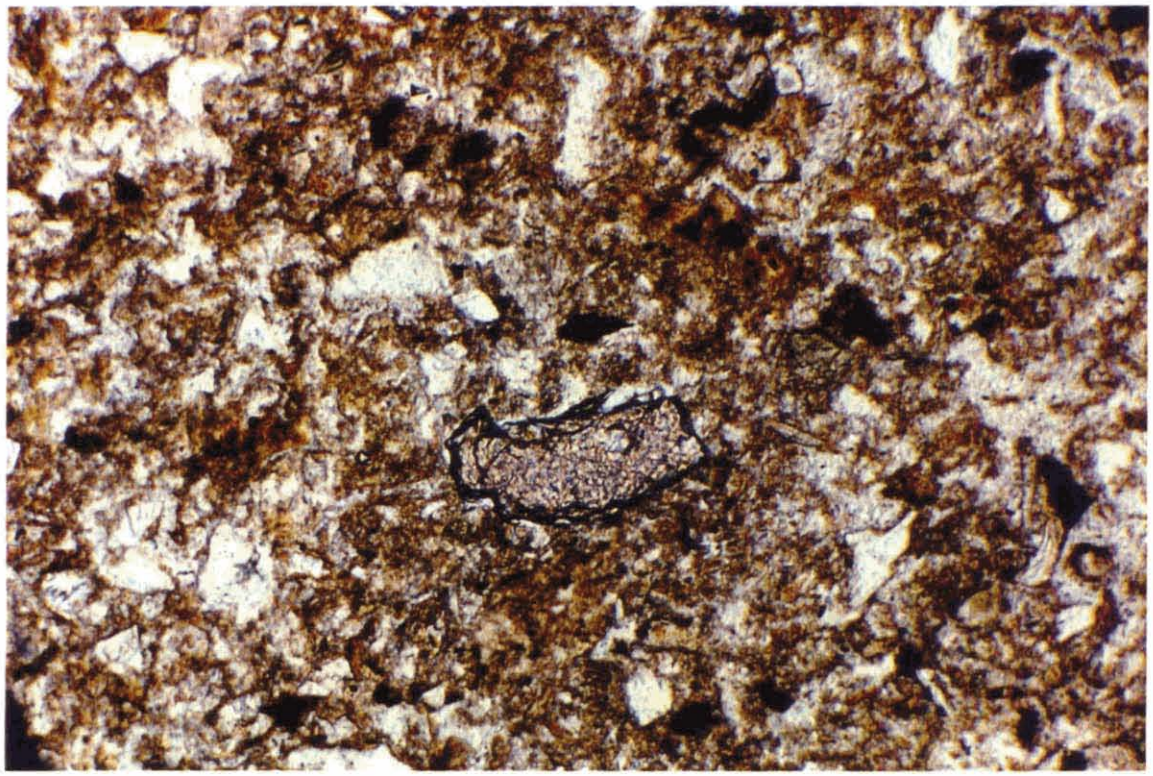
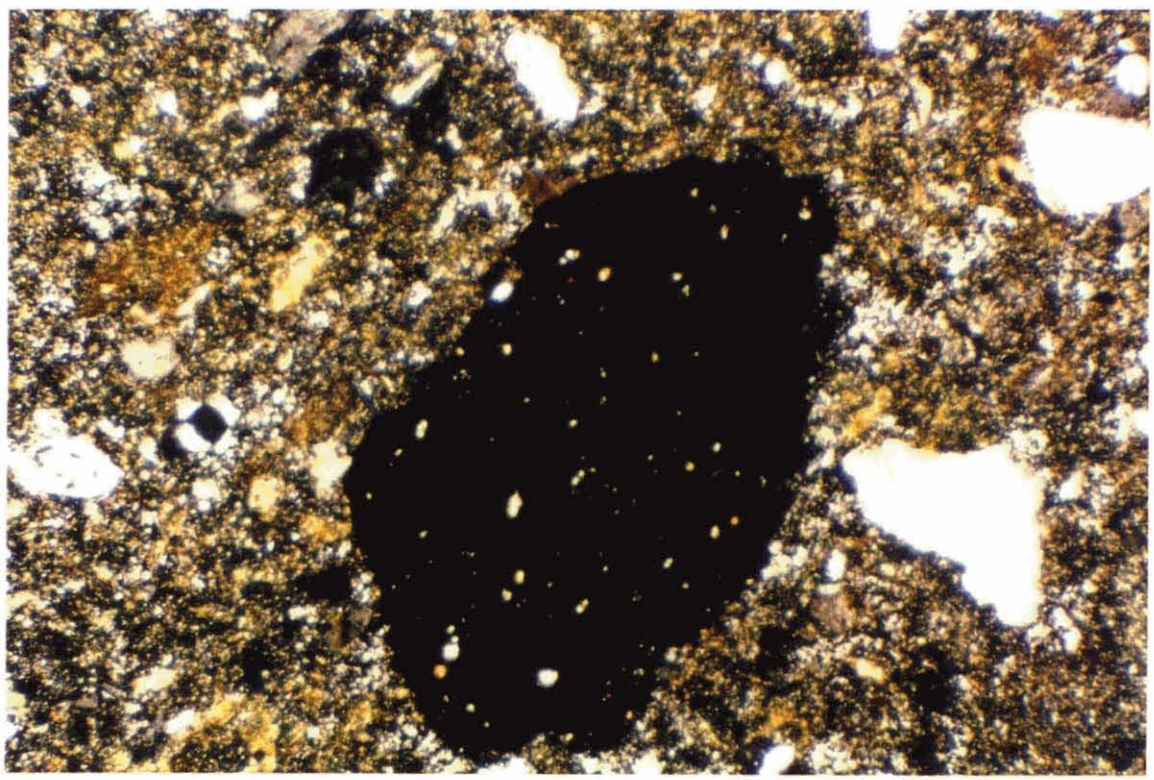


Figure 10

Figure 11



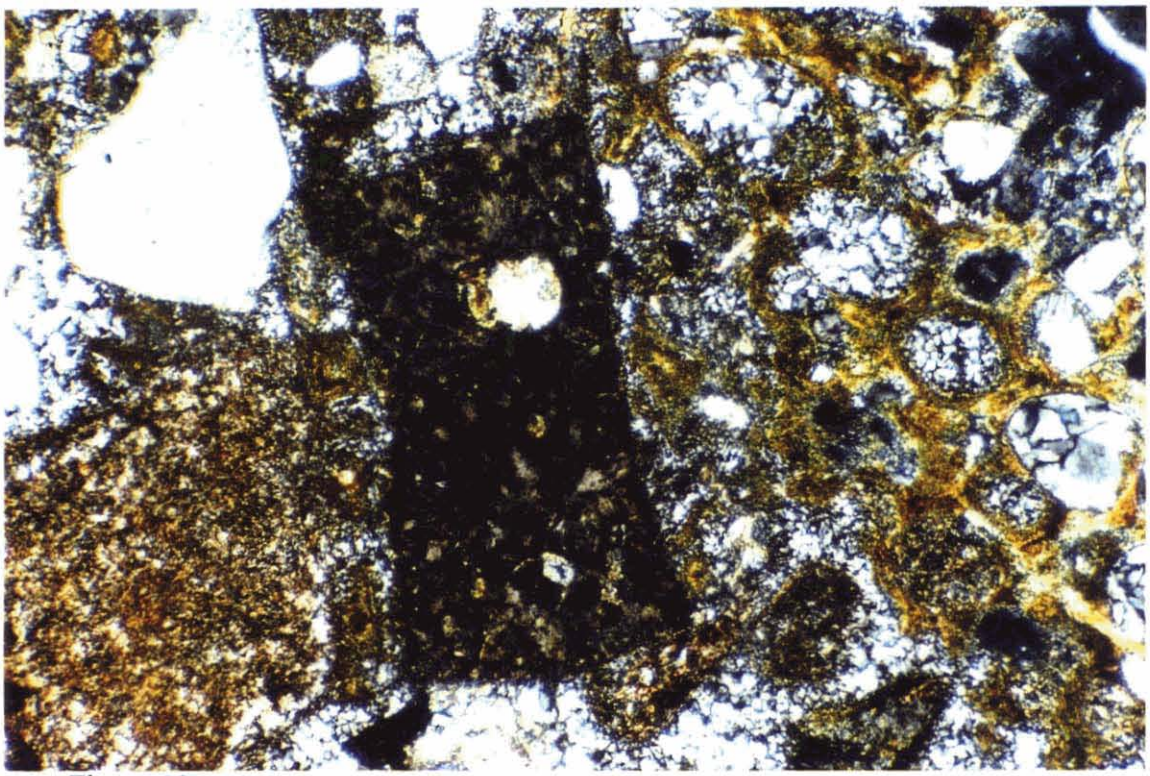
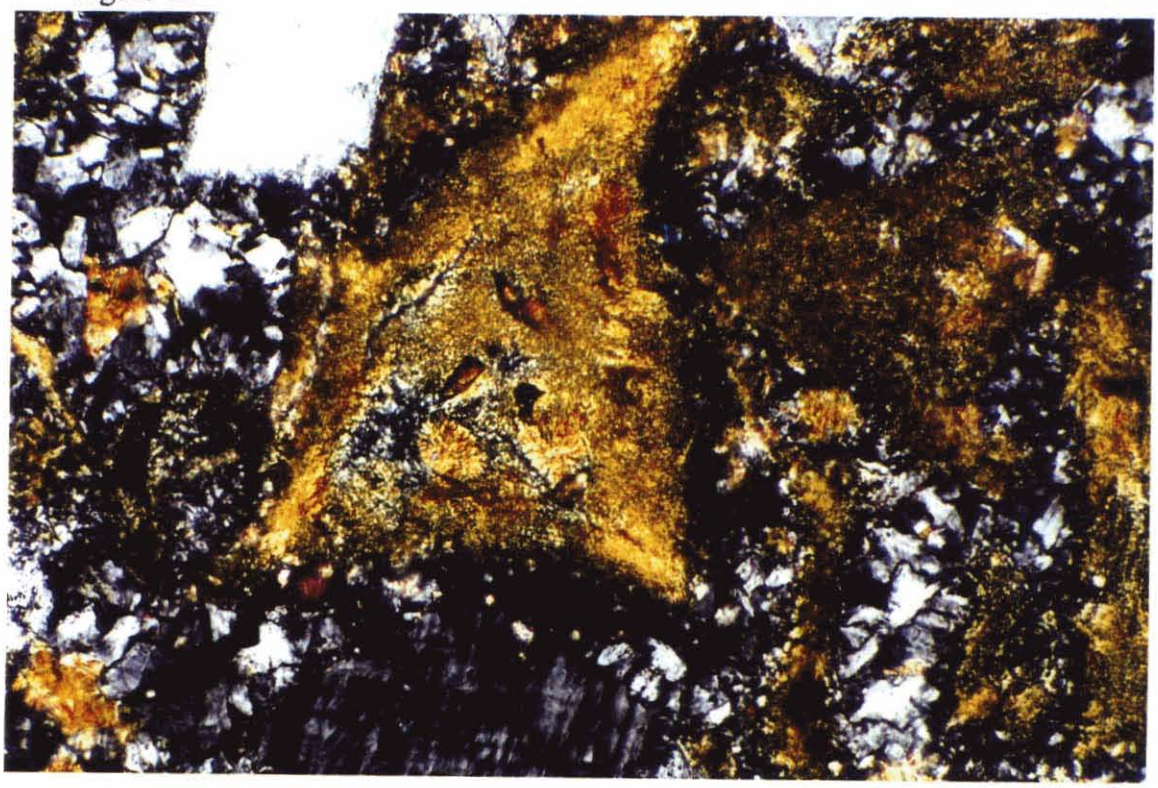


Figure 12

Figure 13



basalt clasts were identified. First, a tan, vesicular fragment with phyllosilicate and zeolite alteration (14-16, 14-18, 14-23 and 14-25). Also, a basalt that is gray-white in color on account of the significant zeolite alteration (14-14, 14-16, 14-25 and 14-33). Other basalt particles include brown, blocky, nearly opaque tachylite and vesicular sideromelane (Fig.12). Much of the groundmass is irresolvable particles. Prismatic zeolite is abundant in matrices and is accompanied by volcanic ash, replaced by phyllosilicate, and minor opaques.

Paleovolcanology

The volcanic processes that formed the pyroclastic rocks of The Mawson Formation can be determined by examining the characteristics of unit. First of all, the peperitic clasts indicate magma interaction with wet sediment prior to eruption (Fisher and Schmincke, 1984; Elliot, 1999). Also, the sandstone and carbonaceous shale xenoliths in the unit match lithologies of the Beacon Supergroup, including quartzose, carbonate sandstones, shales and coals derived from Permian beds. This indicates that magma-sediment interaction occurred at depths of over 500 meters below the surface (Elliot, 1999). The presence of sideromelane and tachylite pyroclasts implies rapid cooling as a result of magma-water interaction. Therefore, these rocks are products of phreatomagmatic activity (Fisher and Schmincke, 1984).

However, the presence of mobile, fluidal basalt blobs, pancakes, shreds and wispy tendrils is evidence of magma disruption by degassing (Bradshaw, 1987; Elliot, 1999). The magma was torn and shredded as bubbles escaped. These pyroclasts represent

periods of decreased explosivity. This type of activity is classified as Hawaiian or Strombolian volcanism.

It has been proposed that the tuff breccias were generated by a slurry of volcanic pyroclasts, and xenoliths erupted directly at the surface, flowing out of the vent, during phreatomagmatic activity (Elliot, 1999). These high energy intervals were followed by quieter periods when magma degassing could occur. The bedded deposits are probably air fall in origin due to the lack of low angle cross stratification. Altogether, these features indicate an uncommon example of phreatomagmatism.

Conclusion

The sequence of tuff breccia, lapilli tuff and tuff that crops out near Thomas Rock in the Prince Albert Mountains has been designated the Mawson Formation. These hydroclastic rocks correlate to the Exposure Hill and the Prebble Formations from other locations in the Transantarctic Mountains and are Middle Jurassic in age. At this time, the foreland basing landscape changed into a tectonic and volcanic regime associated with extension and rifting of Gondwanaland. The volcanogenic process that formed the 50 meter tall formation can be interpreted through examination of the macro and microscopic features of the unit. The abundance of siliciclastic and carbonaceous clasts indicates interaction with beds at depths of 150 to 500 meters (Elliot, 1999). Sideromelane and tachylite represent magma quenching by water. These features suggest phreatomagmatic activity. Yet, the presence of fluidal basalt pyroclasts and basalt "pancakes" throughout the unit suggests quieter intervals where exsolution of gas

occurred. Altogether these elements represent a complex and unique example of phreatomagmatism.

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Appendix A:

Petrographic Descriptions

14-1

A porphyritic rock containing xenocrysts of pyroxene, quartz and potassium feldspar, sedimentary rock fragments, altered basalt grains and tachylite in a fine grained brown matrix of phyllosilicate, zeolite and ash.

minerals (40%)

30% pyroxene- yellow to orange brown xenocrysts, subhedral to anhedral grains sizes up to 0.5 mm.

26% quartz- undulose extinction, subangular to subrounded xenocrysts, anhedral. Grains sizes up to 0.3 mm.

18% tachylite- brown, opaque, vesicles filled by zeolite, sizes up to 4.5 mm.

16% potassium feldspar- subrounded to subangular xenocrysts, some grains show alteration by zeolite or brown phyllosilicate, anhedral. Grain sizes up to 0.25 mm.

8% altered basalt- amygdaloidal, white to light gray in color, alteration to zeolite, brown phyllosilicate and calcite. vesicular, up to 2 mm.

2% sedimentary rock fragment- very fine grained, contains phyllosilicate and plagioclase. sizes up to 5 mm.

matrix (60%) groundmass contains zeolite, ash, and brown phyllosilicate with some secondary calcite and minor opaques.

Rock name: Tuff Breccia

14-3A

A porphyritic rock containing xenocrysts of quartz plagioclase and biotite, sedimentary xenoliths, in a zeolite, ash matrix.

minerals (35%)

35%	quartz- rounded to subrounded, anhedral, undulose extinction. Grains up to 1.0 mm.
30%	phyllosilicate- brown, altering phenocrysts, pyroxene pseudomorph. Grain sizes up to .25mm.
20%	plagioclase- albite twinning, subangular to subrounded, anhedral grains up to 0.6 mm.
13%	potassium feldspar- speckled, dirty appearance, anhedral, subrounded, grains up to 0.5 mm.
2%	sedimentary rock fragment- very fine grained, contains phyllosilicate,
sizes	up to .75 mm.
matrix (65%)	gray brown groundmass consisting of zeolite, ash, secondary calcite and phyllosilicate with minor opaques.

rock name: Lapilli Tuff

14-3B

A porphyritic rock containing xenocrysts of quartz, phyllosilicate, plagioclase, pyroxene and xenoliths in a very fine matrix of zeolite, feldspar laths, and ash.

minerals (40%)

30%	quartz- undulose extinction, subrounded to rounded, grains were dissolved in magma and appear broken, anhedral, sizes up to 1.0 mm.
27%	phyllosilicate- brown, replacing pyroxene, anhedral, grain sizes up to 0.2 mm.
19%	plagioclase- anhedral rounded grains, albite twinning, grains were dissolved in magma and appear broken. Grain sizes up to 0.5 mm.
11%	pyroxene- light orange in color, alteration to biotite, sizes up to 0.75 mm.
7%	opaques- anhedral, grain sizes up to 0.5 mm.
6%	xenolith- fine grained, consists of plagioclase and phyllosilicate up to 1.0 mm.

Matrix (60%) small elongate feldspar laths, zeolite, and ash make up the very fine gray-brown groundmass. secondary alteration by phyllosilicate and calcite.

rock name: Lapilli Tuff

14-3E

A porphyritic rock with xenocrysts of pyroxene, quartz, plagioclase, and potassium feldspar with sideromelane shards in a matrix of zeolite, ash and phyllosilicate.

minerals (40%)

25%	pyroxene- crystals are subhedral to anhedral and slightly yellow in color. Grain sizes up to 0.8 mm.
20%	quartz-undulose extinction, subangular to subrounded and anhedral. Grain sizes up to 0.5mm.
10%	plagioclase-crystals are anhedral, subrounded. Grain sizes up to 0.5 mm.
8%	potassium feldspar- crystals are blocky and anhedral. some alteration. cross-hatched twinning. Grain sizes up to 0.35 mm.
5%	volcanic glass- brown in color, vesicular sizes up to 1.75 mm.
matrix (60%)	gray-brown fine grained groundmass consists of zeolite, and ash. secondary phyllosilicate and calcite altering phenocrysts.

rock name: Lapilli Tuff

14-4A

A slightly vesicular porphyritic rock containing plagioclase, phyllosilicate, and pyroxene with minor opaques, in an orange brown ash, zeolite and phyllosilicate matrix.

minerals (75%)

32%	plagioclase- crystals are elongated laths, subhedral to anhedral. Grain sizes up to 0.5 mm.
30%	phyllosilicate- subhedral to anhedral, brown, sizes up to 0.35 mm.
23%	pyroxene- some orange in color, crystals are subhedral to anhedral. some grains show near right angle cleavage, Grain sizes up to 1.0 mm.
12%	zeolite-crystals are prismatic and colorless, filling vesicles and interstices. Grains sizes up to 1.0 mm.
3%	opaques- minor, blocky, colorless in plain light, sizes up to 0.5 mm.
matrix (25%)	fine grained, orange-brown groundmass containing ash, zeolite and phyllosilicate

rock name: Tuff

14-4B

A porphyritic rock with phenocrysts of plagioclase laths, phyllosilicate and pyroxene with interstitial zeolite in and ash and phyllosilicate matrix.

minerals (75%)

33%	plagioclase- crystals are elongated laths, white to gray in color, subhedral. Grain sizes up to 2.0 mm.
28%	phyllosilicate- brown biotite, crystals are subhedral with sizes up to 2.0 mm.
25%	pyroxene- crystals are subhedral and blocky. Orange to whitish in color. Some right angle cleavage, grain sizes up to 1.0 mm.
20%	zeolite- crystals are white to gray and prismatic, filling vesicles, interstitial, sizes up to 0.75 mm.

matrix (25%) fine grained brown groundmass with ash, phyllosilicate and zeolite.

rock name: Lapilli Tuff

14-5A

A porphyritic, slightly vesicular rock containing plagioclase laths, pyroxene, prismatic zeolite filling vesicles.

minerals (70%)

35%	plagioclase- crystals are elongated and subhedral. Grain sizes up to 1.0 mm.
20%	pyroxene- crystals are brown and subhedral to anhedral. clinopyroxene. Grain sizes up to 2.0 mm.
15%	zeolite- crystals are prismatic and filling vesicles. Grain sizes up to 3.0 mm.
matrix (30%)	gray brown fine grained groundmass containing ash and minor phyllosilicate, secondary prismatic zeolite grown in vesicles.

rock name: Tuff

14-5B

A porphyritic rock with xenocrysts of quartz, pyroxene, phyllosilicate, plagioclase as well as minor opaques and tourmaline in an ash and phyllosilicate matrix with alteration by calcite.

minerals (40%)

30%	quartz- crystals are angular to sub-angular and blocky, undulose extinction. Grain sizes up to 0.25 mm.
28%	pyroxene-brown color, anhedral, subangular to subrounded grains up to 0.30mm.
26%	phyllosilicate- crystals are elongated and anhedral to subhedral. biotite shows compaction by quartz, light brown in color. muscovite also present, colorless. Grain sizes up to 0.45 mm.
10%	plagioclase- crystals are sub-angular to sub-rounded and anhedral. albite twinning, grain sizes up to 0.2 mm.
5%	opaques-blocky and subrounded, grains up to 0.2 mm.
1%	tourmaline- pale green in color, euhedral to subhedral, sizes up to 0.15 mm.
matrix (60%) calcite	fine grained groundmass composed of ash and phyllosilicate matrix, cement.

rock name: Lapilli Tuff

14-5C

A very fine grained rock showing weak layers, xenocrysts of quartz, phyllosilicate and plagioclase with coal fragments in an fine matrix including phyllosilicate and opaques.

minerals (40%)

33%	quartz-crystals are sub-angular to sub-rounded, undulose extinction, grain sizes up to 0.1 mm.
30%	phyllosilicate- brown colored biotite, some elongate grains, anhedral, sizes up to 0.1 mm.
20%	coal- black, opaque, blocky with ragged edges, up to 0.3 mm.
17%	plagioclase- albite twinning, subrounded anhedral grains less than 0.1 mm.

matrix (60%) very fine groundmass consisting of phyllosilicate, coal and other minor opaques.

rock name: Tuff

14-5E

A calcite cemented, quartz rich medium to coarse sandstone with pyroxene, phyllosilicate, plagioclase and potassium feldspar in a matrix of phyllosilicate and minor opaques with calcite cement.

minerals (70%)

30%	quartz- undulose extinction, crystals are subangular to subrounded and blocky. grain sizes up to 2.0 mm.
20%	pyroxene- light brown color, anhedral and subrounded, grain sizes up to .25mm
15%	phyllosilicate- brown colored biotite, bird's eye extinction. grain sizes up to 0.5 mm.
10%	plagioclase-crystals are blocky and subrounded, anhedral, albite twinning. grain sizes up to 0.5 mm.
10%	potassium feldspar- crystals are blocky and dirty in appearance. anhedral, subrounded, grain sizes up to .5mm
matrix (30%)	groundmass consists of phyllosilicate and minor opaques with calcite cement.

rock name: Sandstone Clast (in Tuff Breccia)

14-6

A fine grained rock with abundant carbonaceous grains, quartz, phyllosilicate, plagioclase and amphibole in a very fine matrix of volcanic ash and opaques.

minerals (30%)

28%	coal- black, opaque, ragged edges, sizes up to 0.2 mm.
24%	quartz-crystals are subangular to subrounded, blocky and anhedral, undulose extinction. Grain sizes up to 0.1 mm.
20%	phyllosilicate-elongated brown biotite and colorless muscovite, anhedral to subhedral. Grain sizes up to 0.5 mm.
15%	volcanic glass- sideromelane, orange-brown in color. Grain sizes up to 0.2 mm.
11%	plagioclase- crystals are subangular to subrounded and anhedral. Grain sizes up to 0.1 mm.
2%	amphibole- crystals are subhedral and green in color. Grain sizes up to .25mm

matrix (70%) very fine groundmass of ash, phyllosilicate and minor opaques

rock name: Volcanic Breccia

14-8

A porphyritic rock containing xenocrysts of pyroxene, quartz, phyllosilicate, and plagioclase, as well as carbonaceous fragments, volcanic glass, and altered basalt clasts in a zeolite and ash matrix.

minerals (30%)

25%	quartz- crystals are subangular, blocky and anhedral, undulose extinction. Grain sizes up to 0.5 mm
22%	pyroxene- crystals are blocky and anhedral, light brown in color. Grain sizes up to 0.5 mm.
19%	phyllosilicate- crystals are anhedral and brown in color, some secondary biotite, sizes up to 0.2 mm.
17%	volcanic glass- sideromelane, vesicular, orange brown in color, sizes up 0.7 mm.
12%	plagioclase- subangular crystals, albite twinning, anhedral. Grain sizes up to 0.3 mm.
3%	coal- opaque and black, blocky, irregular in shape. Grain sizes up to 1.0 cm.
2%	altered basalt- gray to white in color, vesicles filled with zeolite, sizes up to 1.2 mm.

matrix (70%) groundmass consists mainly of prismatic zeolite and orange brown ash with secondary calcite and phyllosilicate.

rock name: Lapilli Tuff

14-9

A porphyritic rock containing quartz, volcanic glass, plagioclase, phyllosilicate, pyroxene, carbonaceous grains, potassium feldspar, amphibole, garnet, as well as rhyolitic rock and sedimentary rock fragments in a zeolite and ash matrix.

minerals (40%)

22%	quartz- crystals are subangular to subrounded, blocky and anhedral, undulose extinction. Grain sizes up to 0.75 mm.
18%	volcanic glass- sideromelane orange-brown in color, vesicles filled with zeolite. Grain sizes up to 0.5 mm.
15%	plagioclase- subangular to subrounded blocky, anhedral crystals, albite twinning. Grain sizes up to 0.25 mm.
13%	phyllosilicate- biotite, brown in color, elongated and up to 0.5 mm in length; muscovite, colorless and elongated, up to 0.25 mm in length.
12%	pyroxene- anhedral to subhedral blocky, subrounded to rounded crystals, light brown in color. Grain sizes up to 0.25 mm.
8%	coal- opaque and black in color, irregular, ragged edges. Grain sizes up to 0.5 mm.
4%	potassium feldspar- blocky crystals, exsolution blebs. Grains up to 0.50 mm in size.
3%	amphibole- blocky crystals, green, subhedral to euhedral. Grain sizes up to 0.15 mm.
2%	garnet- opaque crystals, light pink and translucent in plain light. broken and blocky. Grain sizes up to 0.2 mm.
2%	sedimentary xenolith- contains phyllosilicate and plagioclase, sizes up to 2.25 mm.
2%	rhyolitic rock fragment- contains plagioclase and quartz, 3.0 mm.
matrix (60%)	gray brown groundmass consists of prismatic zeolite, ash and minor opaques and phyllosilicate.

rock name: Clastic Dike

14-10

A sub-porphyritic rock with plagioclase, pyroxene and phyllosilicate in a fine ash and minor phyllosilicate matrix.

minerals (25%)

40%	plagioclase- elongated, subhedral to anhedral crystals. Grain sizes up to 0.5 mm.
38%	pyroxene- crystals are subhedral to anhedral and light brown in color. Grain sizes up to 0.5 mm.
22%	phyllosilicate- brown, anhedral, sizes up to 0.5 mm.
matrix (75%)	groundmass is very fine from rapid cooling, but it is not glassy, ash and secondary brown phyllosilicate.

rock name: Tuff

14-14

A porphyritic rock containing volcanic glass, quartz, pyroxene, potassium feldspar, and coal in a zeolite and ash matrix with minor opaques.

minerals (45%)

24%	volcanic glass- sideromelane, vesicular, orange-brown in color, sizes up to 1.0 mm.
20%	quartz- undulose extinction, crystals are broken, blocky and subrounded. Grain sizes up to 0.5 mm.
18%	pyroxene- light brown in color, blocky, anhedral, subrounded grains, Grain sizes up to 0 .75 mm
12%	potassium feldspar- crystals are blocky and subhedral. Grain sizes up to 1.2mm, microcline cross-hatched twinning.
10%	carbonaceous clast- coal, black, opaque, ragged edges, irregular shape. Grain sizes up to 0.75 mm.
8%	altered basalt- white-gray in color, amygdaloidal, secondary alteration by prismatic zeolite rock, sizes up to 1.5 mm.
6%	altered basalt- tan color, amygdaloidal, vesicles filled with prismatic zeolite and brown biotite, sizes up to 3.0 mm.
1%	rock fragment- consists of fine grained phyllosilicate and secondary calcite, sizes up to 3.3 mm.
1%	tachylite- scoriaceous, brown, nearly opaque. sizes up to 0.6 mm.

matrix (55%) finer grained groundmass contains prismatic zeolite, ash and minor opaques with secondary calcite and phyllosilicate.

rock name: Tuff Breccia

14-16

A porphyritic rock containing volcanic glass, quartz, plagioclase, phyllosilicate, potassium feldspar, coal, tan and white basalt pyroclasts and amphibole in a fine grained prismatic zeolite and ash matrix.

minerals (40%)

22%	volcanic glass- sideromelane, brown orange, vesicular and some angular grains, sizes up to 0.5 mm.
20%	quartz-crystals are blocky, subrounded to subangular, undulose extinction, grain sizes up to 1.5 mm.
15%	plagioclase- subrounded grains, albite twinning, anhedral to subhedral. Grain sizes up to 0.4 mm.
14%	phyllosilicate- brown, anhedral grains, some secondary, sizes up to 0.3 mm.
12%	coal-opaque, black, ragged with irregular shape. Grain sizes up to 0.2 mm.
10%	potassium feldspar- exsolution blebs, possibly perthite, grains up to 0.5 mm.
3%	altered basalt- white to gray, amygdaloidal, vesicular, significant alteration by zeolite. Grains up to 0.6 mm.
2%	amphibole-green crystals of hornblende, subhedral, up to .3mm
matrix (60%)	groundmass consists of zeolite, ash and minor opaques, significant alteration by calcite and biotite

rock name: Lapilli Tuff

14-17

A very fine grained clastic rock containing quartz, volcanic glass, phyllosilicate, plagioclase, coal, and pyroxene in a gray ash, phyllosilicate and minor opaque matrix.

mineral (45%)

25%	quartz- subangular to subrounded crystals, undulose extinction. Grain sizes up to 0.1 mm.
24%	volcanic glass- orange brown color, vesicular, some alteration by phyllosilicate. Grain sizes up to 0.45 mm.
15%	phyllosilicate- elongate, anhedral crystals with bird's eye extinction, light brown biotite and colorless muscovite. Grain sizes up to 0.25 mm.
14%	plagioclase-subangular to subrounded anhedral crystals with albite twinning. Grain sizes up to 0.15 mm.
12%	coal- black, opaque and ragged at edges. Blocky irregular grains up to 0.4 mm.
10%	pyroxene- anhedral to subhedral subrounded crystals, light brown in color. Grain sizes up to 0.2 mm.
matrix (55%)	very fine grained groundmass contains ash, phyllosilicate and minor opaques.

rock name: Clastic Dike

14-18

A porphyritic rock consisting of pyroxene, quartz, phyllosilicate, volcanic glass, potassium feldspar, carbonaceous grains, amphibole, garnet, sedimentary xenoliths as well as tan and white altered basalt clasts in a zeolite, ash and minor opaque matrix.

minerals (45%)

22%	pyroxene- light brown anhedral crystals, subrounded, up to 0.5 mm.
18%	quartz- subangular to subrounded crystals, undulose extinction, grains up to 0.5 mm in size.
15%	phyllosilicate- brown, anhedral, mostly secondary, filling vesicles. Grain sizes up to 0.25 mm.
10%	plagioclase-anhedral, tabular crystals, subrounded, albite twinning. Grain sizes up to 0.25 mm.
10%	volcanic glass- sideromelane, vesicular, brown orange in color. few grains elongate, up to 3.0 mm in size.
8%	potassium feldspar- subhedral to anhedral crystals, subrounded, some alteration. Grain sizes up to 0.7 mm.
3%	amphibole- pale green, blocky, subhedral crystals up to 0.2 mm in size.
3%	garnet- isotropic, anhedral crystals with high birefringence, blocky. Grain sizes up to 0.5 mm.
2%	sedimentary xenolith- fine grained with phyllosilicate. Grain sizes up to 2.0 mm.
2%	altered basalt- gray white color, amygdaloidal, vesicular, heavily altered by zeolite. Grain sizes up to 1.5 mm.
1%	altered basalt- tan color, amygdaloidal, vesicular, alteration by zeolite and phyllosilicate. Grain sizes up to 1.25 mm.
matrix (55%)	groundmass consists of prismatic zeolite, volcanic ash and minor opaques. Secondary calcite and zeolite filling vesicles

rock name: Tuff Breccia

14-19

A porphyritic, slightly vesicular, rock containing phenocrysts of pyroxene, elongated plagioclase, phyllosilicate, volcanic glass and interstitial zeolite in an ash, phyllosilicate and plagioclase lath matrix.

minerals (30%)

28%	pyroxene- light brown, subhedral to anhedral crystals up to 0.5 mm.
26%	plagioclase-elongate laths up to 0.3 mm in length.
23%	phyllosilicate- anhedral to subhedral, brown, secondary, sizes up to 0.2 mm.
15%	volcanic glass-sideromelane, vesicular, brown orange in color, up to 0.1 mm in size.
8%	zeolite- colorless, prismatic, secondary, filling vesicles. Grain sizes up to 0.2 mm.

matrix (70%) fine brown groundmass contains ash, phyllosilicate and microphenocrysts of plagioclase

rock name: Basalt Clast

14-20

A porphyritic slightly vesicular rock containing pyroxene, plagioclase, volcanic glass shards, potassium feldspar and secondary zeolite in a fine grained ash, phyllosilicate and minor opaque matrix.

minerals (30%)

25%	pyroxene- anhedral and angular crystals, some alteration to phyllosilicate, pseudomorph, sizes up to 1.5 mm.
22%	plagioclase- elongate laths, anhedral, up to 0.25 mm in size.
20%	volcanic glass- sideromelane, brown orange, sizes up to 0.4 mm.
15%	phyllosilicate- anhedral, brown, elongate biotite crystals. Grain sizes up to 0.3 mm.
10%	potassium feldspar-anhedral blocky crystals with some alteration. Grain sizes up to 0.9 mm.
8%	zeolite- colorless, prismatic secondary, filling vesicles. Grain sizes up to 0.5 mm.
matrix (70%)	very fine brown groundmass cooled rapidly but is not glassy. Consists of ash, phyllosilicate and minor opaques.

rock name: Basalt Clast

14-21

A medium to coarse grained clastic rock with abundant quartz and feldspar as well as pyroxene, phyllosilicate and garnet in a dark matrix with calcite cement.

minerals (85%)

40%	quartz- large fragmented grains, subangular to subrounded, undulose extinction. Grain sizes up to 3.5 mm.
35%	potassium feldspar- subangular to subrounded grains up to 3.0 mm in size, microcline determined by cross-hatched twinning.
12%	pyroxene- anhedral to subhedral light brown crystals, subrounded, sizes up to 0.25 mm.
11%	phyllosilicate- anhedral to subhedral, colorless muscovite and brown biotite, bird's eye extinction. Grain sizes up to 0.25 mm.
2%	garnet-high birefringent, isotropic blocky crystals up to 0.1 mm.

matrix (25%) dark groundmass containing opaques, phyllosilicate and calcite cement.

rock name: Arkose Sandstone Clast in Tuff

14-22

A very fine grained sub-porphyritic rock containing quartz, phyllosilicate, plagioclase, volcanic glass, carbonaceous clasts, zeolite and amphibole in a brown ash and phyllosilicate matrix.

minerals (40%)

32%	quartz- undulose extinction, subhedral, angular to subangular crystals up to 0.1 mm.
25%	phyllosilicate- brown, subhedral grains, some elongated. Grain sizes up to 0.5 mm.
20%	plagioclase- anhedral to subhedral crystals, albite twinning, subrounded, sizes up to 0.15 mm.
10%	volcanic glass- sideromelane pyroclast, brown orange in color, vesicular, Grain sizes up to 0.35 mm.
8%	coal- black, opaque, ragged and blocky. Grain sizes up to 0.6 mm.
3%	zeolite- colorless prismatic grains filling vesicles. Grain sizes up to 0.25 mm.
2%	amphibole- pale green blocky crystals up to 0.15 mm.
matrix (60%)	brown groundmass consists of phyllosilicate and ash with secondary calcite and zeolite.

rock name: Tuff and Lapilli Tuff

14-23

A porphyritic rock containing volcanic glass, pyroxene, quartz, phyllosilicate, plagioclase, coal xenoliths, and altered basalt pyroclasts in a ash, zeolite opaques matrix.

minerals (45%)

33%	volcanic glass- sideromelane, orange brown in color, vesicular, some stretched vesicles. Grain sizes up to 0.3 mm.
20%	pyroxene- subhedral to anhedral light brown xenocrysts up to 0.55 mm.
15%	quartz- undulose extinction, subangular to subrounded anhedral crystals up to 0.2 mm in size.
12%	phyllosilicate- brown colored elongate biotite, also secondary phyllosilicate. Grain sizes up to 0.5 mm.
10%	plagioclase- subrounded, subhedral grains, albite twinning, sizes up to 0.25 mm.
5%	coal xenolith- opaque, black, irregular and blocky. Grain sizes up to 0.45 mm.
3%	altered basalt- white to gray in color, amygdaloidal, highly altered by zeolite. Grain sizes up to 1.0 mm.
2%	altered basalt- tan color, amygdaloidal, vesicles filled with zeolite and phyllosilicate. Grain sizes up to 1.2 mm.
matrix (55%)	groundmass consists of ash, zeolite and mineral grains with carbonaceous particles as well as secondary calcite.

rock name: Tuff and Lapilli Tuff.

14-24

A porphyritic rock with volcanic glass, quartz, pyroxene, plagioclase, potassium feldspar, biotite, amphibole and garnet in a zeolite, ash and phyllosilicate matrix

minerals (40%)

30%	volcanic glass- sideromelane, brown orange, vesicular, grains up to 0.4 mm.
20%	quartz- undulose extinction, subrounded to subangular blocky crystals up to 0.75 mm in size.
15%	pyroxene- subhedral to anhedral light brown, subrounded crystals up to 0.5 mm.
12%	plagioclase- subhedral, subrounded, albite twinning. Grain sizes up to 0.25 mm.
10%	potassium feldspar-blocky, anhedral. Grain sizes up to 0.25 mm.
10%	phyllosilicate- brown, anhedral grains up to 0.25 mm.
2%	amphibole- pale green crystals, subhedral, up to 0.2 mm.
1%	garnet- isotropic, subhedral, high birefringence, grains up to 0.1mm.
matrix (60%)	groundmass contains prismatic zeolite, ash and phyllosilicate with secondary calcite and minor opaques.

rock name: Tuff and Lapilli tuff

14-25

A porphyritic rock with quartz, pyroxene, volcanic glass, plagioclase, phyllosilicate, potassium feldspar, sedimentary xenoliths, tachylite, altered basalt and amphibole in a zeolite, ash and opaque matrix.

minerals (40%)

21%	quartz- subangular to subrounded, blocky crystals, undulose extinction, sizes up to 0.75 mm.
15%	pyroxene- subrounded, light brown, anhedral grains up to 0.6 mm.
13%	volcanic glass- sideromelane, orange brown, vesicular, sizes up to 0.8 mm.
11%	plagioclase- anhedral, subangular to subrounded, albite twinning, sizes up to 0.3 mm.
11%	potassium feldspar- anhedral, blocky, cross-hatched twinning indicates microcline, up to 0.5mm.
9%	phyllosilicate- brown, anhedral. Grain sizes up to 0.2 mm.
7%	sedimentary xenoliths- fine grained rock with phyllosilicate. Sizes up to 1.5 mm.
6%	altered basalt- white/gray and tan, amygdaloidal, alteration by zeolite and/or biotite. Grain sizes up to 1.0 mm.
5%	tachylite- brown, scoriaceous, some alteration. Grain sizes up to 0.4 mm.
2%	amphibole- pale green, subhedral to anhedral, sizes up to 0.3 mm.
matrix (60%)	groundmass is made up of prismatic zeolite and very fine ash with carbonaceous grains, some secondary calcite.

rock name: Tuff Breccia

14-26

A porphyritic rock with quartz, pyroxene, volcanic glass, plagioclase, phyllosilicate, potassium feldspar, sedimentary xenoliths, altered basalt, coal, tachylite, amphibole and garnet in a zeolite and ash matrix with minor opaques.

minerals (40%)

18%	quartz- undulose extinction, subangular to subrounded large grains up to 1.0 mm.
16%	pyroxene- anhedral, subrounded grains, sizes up to 1.6 mm.
15%	volcanic glass- vesicular, brown orange. Grain sizes up to 1.0 mm.
12%	plagioclase- subangular to subrounded, anhedral grains, albite twinning, sizes up to 0.5 mm.
11%	phyllosilicate- mainly secondary brown, anhedral. Grain sizes up to 0.4 mm.
9%	potassium feldspar- cross hatched twinning of microcline and exsolution blebs in perthite, subangular to subrounded, anhedral, sizes up to 1.25 mm.
6%	sedimentary xenolith- very fine grained, some phyllosilicate observed. xenoliths up to 3.0 mm
5%	altered basalt- both white/gray and tan, amygdaloidal, alteration by zeolite and phyllosilicate. Grain sizes up to 1.75 mm.
4%	coal- opaque, black, ragged and irregular, sizes up to 0.75 mm.
2%	tachylite- brown, scoriaceous, some alteration. Grain sizes up to 0.5 mm.
1%	amphibole- pale green, subhedral to anhedral. Grain sizes up to 0.25 mm.
1%	garnet- isotropic, high birefringence, subhedral to anhedral, sizes up to 0.2 mm.

matrix (60%) groundmass contains prismatic zeolite, fine volcanic ash, and opaques with secondary calcite.

rock name: Lapilli Tuff

14-27

A porphyritic rock with quartz, pyroxene, phyllosilicate, plagioclase, volcanic glass, potassium feldspar and garnet in a matrix of ash, zeolite, phyllosilicate and opaques.

minerals (25%)

25%	quartz- undulose extinction, subangular to subrounded, sizes up to 0.5 mm.
20%	pyroxene- subangular to subrounded, light brown, some alteration. Grain sizes up to 0.25 mm.
18%	phyllosilicate- secondary, brown. Grain sizes up to 0.25 mm.
16%	plagioclase- subrounded, anhedral, albite twinning. Grains up to 0.15 mm.
10%	volcanic glass- orange brown color, vesicular, translucent, sizes up to 0.2 mm.
9%	potassium feldspar- subrounded, anhedral, alteration by calcite. Grain sizes up to 1.0 mm.
2%	garnet- isotropic, high birefringence, blocky, anhedral, sizes up to 0.15 mm.

matrix (75%) groundmass is made up of prismatic, colorless zeolite, fine ash, phyllosilicate and minor opaques.

rock name: Lapilli Tuff

14-28

A porphyritic rock containing quartz, pyroxene, volcanic glass, plagioclase, potassium feldspar, phyllosilicate, coal, other sedimentary xenoliths and garnet with secondary calcite in a zeolite, ash and phyllosilicate matrix with minor opaques.

minerals (45%)

20%	quartz- undulose extinction, subangular to subrounded, grains up to 1.5 mm.
17%	pyroxene- subangular to subrounded, light brown grains up to 0.5 mm.
16%	volcanic glass- sideromelane, translucent brown, stretched vesicles, sizes up to 0.7 mm.
14%	plagioclase- subrounded, anhedral, albite twinning. Grain sizes up to 0.2 mm.
12%	potassium feldspar- anhedral to subhedral, microcline cross-hatched twinning, sizes up to 0.5 mm.
8%	phyllosilicate- colorless muscovite and brown biotite, anhedral, bird's eye extinction. Grains up to 0.25 mm.
6%	coal- black, opaque, irregular and ragged. Grains up to 0.4 mm.
4%	sedimentary xenolith- fine grained, contains phyllosilicate, size up to 0.75 mm.
3%	garnet- elongate, rectangular, isotropic, high birefringent. Grain sizes up to 0.35 mm

matrix (55%) ground mass contains prismatic, colorless zeolite, fine ash, phyllosilicate an opaques with secondary calcite.

rock name: Lapilli Tuff

14-29

A fine grained rock containing quartz, volcanic glass, plagioclase, pyroxene, phyllosilicate, potassium feldspar, coal, other sedimentary xenoliths, amphibole and garnet with secondary calcite in a zeolite, ash matrix with minor opaques.

minerals (40%)

22%	quartz- undulose extinction, subangular to subrounded, grains up to 0.3 mm.
18%	volcanic glass- shards, translucent brown, stretched vesicles, sizes up to 0.1 mm.
15%	plagioclase- subrounded, anhedral, albite twinning. Grain sizes up to 0.2 mm.
12%	pyroxene- subangular to subrounded, light brown grains up to 0.15 mm.
10%	phyllosilicate- colorless muscovite and brown biotite, subhedral, bird's eye extinction. Grains up to 0.25 mm.
8%	potassium feldspar- anhedral, subrounded to subangular grains up to 0.2 mm.
7%	coal- black, opaque, irregular and ragged. Grains up to 0.25 mm.
5%	sedimentary xenolith- fine grained, contain phyllosilicate, size up to 0.3 mm.
2%	amphibole- pale green, subhedral to anhedral, sizes up to 0.15 mm.
1%	garnet- elongate, rectangular, isotropic, high birefringent. Grain sizes up to 0.25 mm.

matrix (55%) ground mass contains prismatic, colorless zeolite, fine ash, and blocky opaques. Some calcite alteration

rock name: Lapilli Tuff

14-30

A porphyritic rock containing quartz, volcanic glass, pyroxene, plagioclase, phyllosilicate, potassium feldspar, coal, other sedimentary xenoliths, amphibole and garnet with secondary calcite in a matrix of zeolite, ash and minor opaques.

minerals (45%)

21%	quartz- undulose extinction, subangular to subrounded, grains up to 0.5 mm.
19%	volcanic glass- shards, translucent brown, stretched vesicles, alteration by phyllosilicate, sizes up to 0.1 mm.
15%	pyroxene- subangular to subrounded, light brown grains up to 0. 5 mm.
13%	plagioclase- subangular, anhedral, albite twinning. Grain sizes up to 0.25 mm.
12%	phyllosilicate- anhedral brown biotite and muscovite, bird's eye extinction. Grains up to 0.5 mm.
10%	potassium feldspar- anhedral, subrounded to subangular, microcline cross hatched twinning, grains up to 0.25 mm.
6%	coal- black, opaque, irregular and ragged. Grains up to 0.55 mm.
2%	sedimentary xenolith- fine grained, contains phyllosilicate, size up to 0.3 mm.
1%	amphibole- pale green, subhedral to anhedral, sizes up to 0.25 mm.
1%	garnet- elongate, rectangular, isotropic, high birefringent. Grain sizes up to 0.15 mm

matrix (55%) ground mass contains prismatic, colorless zeolite, fine ash, and blocky opaques. Significant alteration by calcite.

rock name: Lapilli Tuff

14-31

A fine grained rock containing quartz, pyroxene, plagioclase, potassium feldspar, phyllosilicate, volcanic glass shards, coal, other sedimentary xenoliths, amphibole and garnet in a matrix of zeolite, ash and minor opaques.

minerals (25%)

24%	quartz- undulose extinction, angular to subangular, broken, grains up to 0.3 mm.
20%	pyroxene- subangular to subrounded, light brown grains up to 0.5 mm.
15%	plagioclase- angular to subangular, anhedral, albite twinning. Grain sizes up to 0.2 mm.
11%	potassium feldspar- anhedral, subrounded to subangular, microcline cross hatched twinning, grains up to 0.3 mm.
10%	phyllosilicate- anhedral brown biotite, bird's eye extinction. Grains up to 0.15 mm.
9%	volcanic glass- shards, translucent brown, stretched vesicles, alteration by phyllosilicate, sizes up to 0.25 mm.
5%	coal- black, opaque, irregular and ragged. Grains up to 0.75 mm.
3%	sedimentary xenolith- fine grained mudstone, contains phyllosilicate, size up to 0.5 mm.
2%	amphibole- pale green, subhedral to anhedral, sizes up to 0.25 mm.
1%	garnet- elongate, anhedral, isotropic, high birefringent. Grain sizes up to 0.4 mm.

matrix (55%) ground mass contains prismatic, colorless zeolite, fine ash, and minor opaques.

rock name: Tuff

14-32

A porphyritic rock consisting of quartz, plagioclase, pyroxene, phyllosilicate, potassium feldspar, garnet in a matrix of zeolite, phyllosilicate, ash, and minor opaques.

minerals (40%)

28%	quartz- undulose extinction, subrounded to subangular, grains up to 1.0 mm.
22%	plagioclase- angular to subangular, anhedral, albite twinning. Grain sizes up to 0.5 mm.
20%	pyroxene- subangular to subrounded, light brown grains up to 1.0 mm.
18%	phyllosilicate- anhedral brown biotite, secondary. Grains up to 0.15 mm.
10%	potassium feldspar- subhedral to anhedral, subrounded, microcline cross hatched twinning, grains up to 1.0 mm.
2%	garnet- subhedral, isotropic, high birefringent. Grain sizes up to 0.2 mm

matrix (55%) ground mass contains prismatic, colorless zeolite, phyllosilicate and minor opaques.

rock name: Lapilli Tuff

14-33

A porphyritic rock containing quartz, pyroxene, volcanic glass shards, plagioclase, phyllosilicate, potassium feldspar, sedimentary xenoliths, altered basalt, tachylite and garnet in a matrix of zeolite, ash and minor opaques.

minerals (25%)

20%	quartz- undulose extinction, subrounded to subangular, grains up to 1.0 mm.
17%	pyroxene- subrounded, light brown grains up to 0.5 mm.
16%	volcanic glass- shards, translucent brown, vesicular, alteration by phyllosilicate, sizes up to 0.25 mm.
12%	plagioclase- subangular, anhedral, albite twinning. Grain sizes up to 0.25 mm.
10%	phyllosilicate- anhedral brown, secondary, altering glass. Grains up to 0.15 mm.
8%	potassium feldspar- anhedral, subrounded to subangular, microcline cross hatched twinning, some orthoclase, grains up to 0.15 mm.
6%	sedimentary xenolith- opaque, carbonaceous, phyllosilicate shreds, size up to 1.0 mm.
5%	altered basalt- white and tan, alteration by zeolite and biotite, vesicular, sizes up to 1.6 mm.
4%	tachylite- scoriaceous, rectangular, opaque. Sizes up to 0.6 mm.
2%	garnet- elongate, anhedral, isotropic, high birefringent. Grain sizes up to 0.1 mm.

matrix (65%) ground mass consists of prismatic, colorless zeolite, fine ash, and minor opaques.

rock name: Tuff Breccia